MICROWAVE LINK PHASE COMPENSATION FOR LONGITUDINAL STOCHASTIC COOLING IN RHIC*

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Abstract

A new microwave link has been developed for the longitudinal stochastic cooling system, replacing the fiber optic link used for the transmission of the beam signal from the pickup to the kicker. This new link reduces the pickup to kicker delay from 2/3 of a turn to 1/6 of a turn, which greatly improves the phase margin of the system and allows operation at higher frequencies. The microwave link also introduces phase modulation on the transmitted signal due to variations in the local oscillators and time of flight. A phase locked loop tracks a pilot tone generated at a frequency outside the bandwidth of the cooling system. Information from the PLL is used to calculate real-time corrections to the cooling system at a 10 kHz rate. The design of the pilot tone system is discussed and results from commissioning are described.

INTRODUCTION

In the Relativistic Heavy Ion Collider (RHIC), intra-beam scattering (IBS) is a primary cause of emittance growth of the gold beam. The stochastic cooling system is a wide band feedback loop designed to combat IBS and reduce the emittance of the beam.

A longitudinal stochastic cooling system was commissioned in the Yellow ring at RHIC in 2007 [1] and used during the FY07 and FY08 runs. The pickup for this system was in the 12 o'clock straight section, and the kicker was in the 4 o'clock straight section. As the beam travelled counter-clockwise, the pickup signal was transmitted on an analog fiber optic link through the tunnel. The pickup to kicker delay was 2/3 of a turn.

Prior to the FY09 run, a new longitudinal system was installed in the Blue ring. This system had the pickup located in the 2 o'clock region and the kicker at 4 o'clock. A microwave link connected them, with the transmitter installed on the berm above the beamline and the receiver located on the roof of the RF service building. The Blue beam travels clockwise, so the delay from pickup to kicker is 1/6 of a turn. The FY09 run was dedicated to polarized protons, so while important R&D work was completed, the new longitudinal cooling system was not made operational.

During the 2009 summer shutdown, the existing longitudinal cooling system in the Yellow ring was removed, and an upgraded system using the microwave link was reinstalled. The pickup was now located in the 2 o'clock straight section, with the kicker in the 12 o'clock region. Systems for vertical cooling were also installed in both rings. The vertical cooling systems use fiber optic links to transmit the signal from the pickups to the kickers.

The Blue and Yellow longitudinal stochastic cooling systems were both successfully commissioned during the FY10 100 GeV/nucleon gold run. Blue cooling was used in routine operation. Yellow cooling was successfully tested, but a series of mechanical problems with the kicker prevented routine operation. A schematic representation of the locations of the system components, along with the links between them, is shown in figure 1.

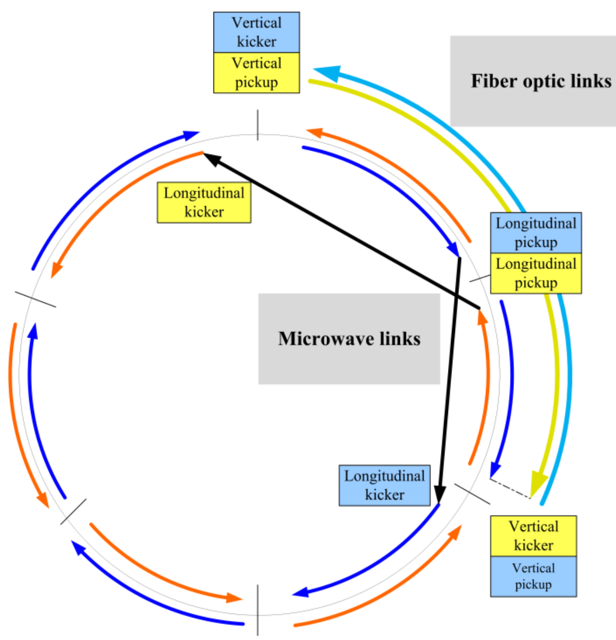

Figure 1: Locations of pickups and kickers (blue and yellow boxes), longitudinal system microwave links (black arrows), and vertical system fiber optic links (light blue and yellow arrows). The dark blue and orange arrows indicate the direction the beams travel.

EFFECT OF PICKUP TO KICKER DELAY

The longitudinal cooling system uses a one-turn delay notch filter to determine the kick necessary for cooling. The signal from the previous turn is subtracted from the current signal. This filter has the transfer function $G_1(f) = [1 - \exp(2\pi i \Delta f T_0)]\exp(2\pi i \Delta f T_d)$, where T_0 is the revolution period, T_d is the pickup to kicker delay, and Δf is the difference between the drive frequency and the nearest revolution line.

With the 2/3 of a turn delay of the fiber optic link and the one-turn filter, the cooling force has the correct sign for $|\Delta f| \leq 16.5$ kHz [2]. For gold beam with γ = 107 and 4 MV on the RF storage cavities at h = 2520 the

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frequency spread at the edge of the bucket is

$$\frac{\Delta f}{f_{sys}} = \eta \frac{\Delta p}{p} = \pm 2.8 \times 10^{-6}$$

where f_{sys} is the operating frequency of the cooling system, $\Delta p/p$ equals $\pm 1.5 \times 10^{-3}$ is the momentum spread, and η equals 1.82×10^{-3} is the frequency slip parameter. This would have limited a one-turn delay cooling system to an upper frequency of 5.9 GHz. Instead, the previous system used a two-turn delay filter [3] to extend the stable part of the cooling force to a larger frequency spread, at the expense of reduced cooling in the center of the bunch. The maximum stable frequency for this system was 8.3 GHz, and the highest kicker frequency used was 8.0 GHz.

By reducing the pickup to kicker delay to 1/6 of a turn, the cooling force has the correct sign for $|\Delta f| \leq 29.3$ kHz. This increases the maximum stable frequency to 10.4 GHz. The highest kicker frequency used in the current system is 9.0 GHz. The cooling force for the different pickup to kicker delays and filters are compared in figure 2.

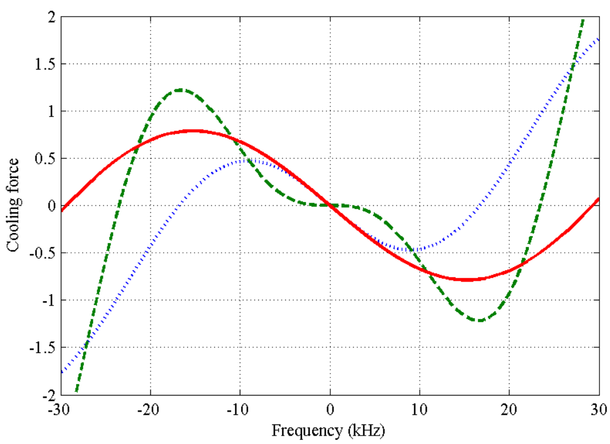

Figure 2: Cooling force for one-turn (blue dots) and two-turn (green dashes) filters with 2/3 turn pickup to kicker delay and for one-turn (red solid) filter with 1/6 turn pickup to kicker delay

THE MICROWAVE LINK

The microwave link is adapted from a commercial product for point-to-point wireless links for Gigabit Ethernet [4]. It operates via amplitude modulation in the 70 GHz E-band, with synchronous up and down conversions at the transmitter and receiver. The local oscillator is generated in an alcove in the tunnel at approximately the midpoint between the transmitter and receiver. The signal is distributed by fiber optics to both ends of the link.

New longitudinal pickups were installed during the 2009 shutdown. These pickups consist of ceramic windows in the beam pipe with waveguide to coax adapters. Previously, we had used planar array pickup devices built for stochastic cooling tests in the Tevatron [5]. The new pickups do not have any moving parts inside the vacuum, greatly simplifying their mechanical design

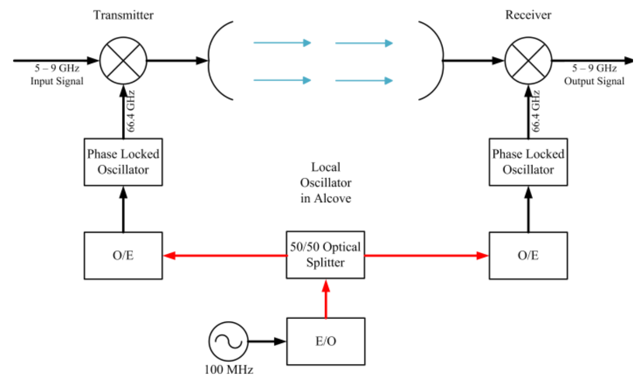

Figure 3: Microwave link signal distribution

and reducing the possibility of vacuum leaks. The signals from the inside and outside waveguide adapters are summed and routed directly to an electronics rack suspended from the ceiling of the tunnel. This rack contains a digitally controlled step attenuator, preamplifier, and the traversal filter [3]. The fiber optic receiver for the local oscillator is also located in this rack. The signal and local oscillator are then routed through a port in the roof of the tunnel to the microwave transmitter. The microwave signal is down converted by the receiver and fed to the input of the notch filter. The cable lengths for all of these connections are kept as short as possible to minimize delay. After optimizing the rack layouts and cable and fiber lengths, the signal arrives at the kicker within 10 ns of the optimal time. The traversal filter stretches the bunch signal to 80 ns, so the small extra delay is acceptable.

Microwave Link Phase Modulation

The microwave link introduces variations in the phase of the signal at the receiver. One source of phase modulation is variations in the time of flight from the transmitter to the receiver. A pure time delay of the received signal is modelled as $G_p(\omega) = \exp\left(iT_p\omega\right)$, where T_p is the propagation delay of the link. This results in a phase shift that increases linearly with frequency. Another source is phase shift of the local oscillators. The up conversion and down conversion can be modelled as

$$x_r(t) = x_t(t)\exp\left(i(\omega_{LO}t + \varphi_t)\right)\exp\left(-i(\omega_{LO}t + \varphi_r)\right) = x_t(t)\exp\left(i(\varphi_t - \varphi_r)\right)$$

where $x_t(t)$ is the transmitted signal, $x_r(t)$ is the received signal, and φ_t and φ_r are the local oscillator phases at the transmitter and receiver. This results in a phase shift that is constant at all frequencies.

Fluctuations in the phase of the kicker signal reduce the phase margin of the system and can decrease the efficiency of the cooling. An out of band pilot tone is generated, and a phase locked loop (PLL) is used to compensate the fluctuations in the link.

THE PILOT TONE

A CW 5.075 GHz tone is generated in the service building that houses the electronics at the receiving end of the microwave link. The operating frequency of the pilot tone was selected to align with one of the nulls of the traversal filter at the pickup in order to reduce interference. This signal is split and one branch is connected to an electrical to optical converter. This signal is sent over a fiber optic link to the pickup electronics in the tunnel, where it is converted back to an electrical signal, amplified and added to the pickup signal with a directional coupler. This combined signal is then transmitted by the radio.

The received signal is passed through a 20 dB directional coupler, with the main branch connected to the input of the one-turn delay notch filter. The coupled signal is connected to a preamplifier with a bandpass filter centered at the pilot tone frequency. The signal is phase shifted by an I/Q vector modulator, and connected back to the module that generates the pilot tone.

The pilot tone module contains a mixer and low-pass filter which detect the phase difference between the received pilot tone signal and the signal split from the generator. The bandwidth of the phase detector is 15 kHz. A block diagram of the RF hardware is shown in figure 4.

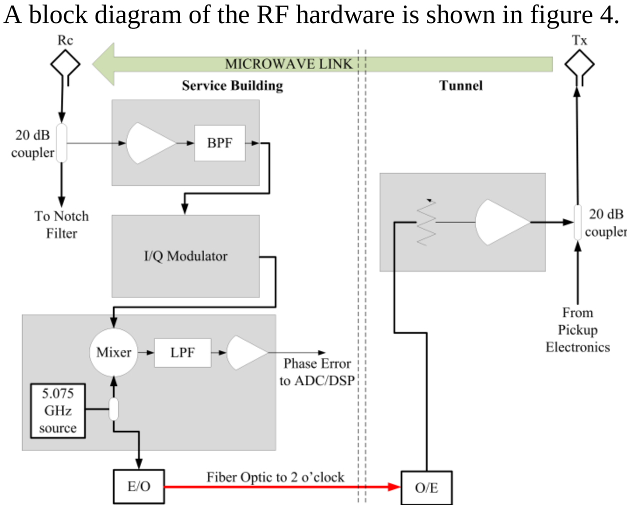

Figure 4: Block diagram of pilot tone RF hardware

The phase detector output is connected to a DSP carrier board in the VME chassis that contains the front-end computer (FEC) for the low-level control of the system. This DSP carrier board was originally designed for the AGS Booster [6], and was modified for this application.

The DSP carrier board contains an Analog Devices ADSP-21160, logic for the VME bus interface, local RAM that is shared with the VME bus master, and two daughter card sites. One of these sites is populated with a 4 channel ADC daughter card, which contains 4 AD9245 14-bit analog to digital converters and an Altera Stratix FPGA.

The FPGA acquires the phase detector data from the ADC at 40 MSPS, and filters it with a first-order IIR filter with 3 kHz bandwidth. The DSP reads the phase data from the FPGA at 10 kHz, and calculates a phase

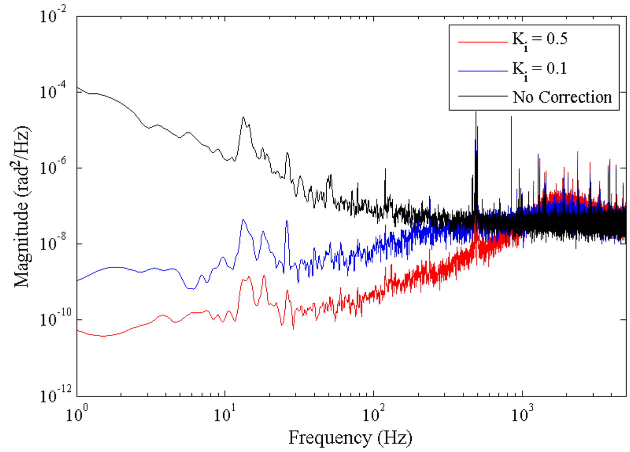

Figure 5: Power spectral density of phase error signal with pilot tone correction off (black) and on with integral gains of 0.1 (blue) and 0.5 (red)

correction with a PID loop. The normal configuration for the system only uses integral gain, and sets the proportional and derivative gains to zero. The pilot tone PLL is stable with a bandwidth up to approximately 1 kHz. The performance of the PLL is shown in figure 5.

System Corrections

The PLL applies a phase shift to the received pilot tone signal to cancel the phase shift from the link, but in order to improve the performance of the cooling system a correction must be applied to the drive signal for each of the 16 kicker cavities.

The low level system contains an I/Q modulator for each of the cavities. The settings for these modulators are determined by measuring the beam transfer function (BTF), and correcting the amplitude and phase to match a reference response [7]. This correction is performed every 10 to 15 minutes. These corrections are calculated by the FEC.

The I/Q modulator settings are distributed over a local serial bus. This bus, known as the NIM Link, originates from the Stratix FPGA on the ADC daughter card. The 10

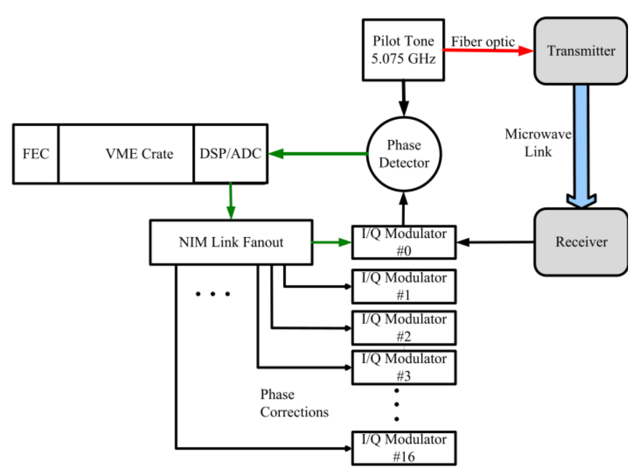

Figure 6: Block diagram of pilot tone phase compensation system

Mbps, biphase mark protocol is similar to the Real Time Data Link (RTDL) used throughout the RHIC complex, and the daughter card was modified to include a differential line driver so that the same fanout hardware and type of cabling can be used.

The initial belief was that the dominant source of phase shift would be the time of flight variation in the link. The initial DSP implementation calculated a frequency dependent phase shift $\varphi(f_{cav}) = (f_{cav}/f_{pilot})\varphi_{pilot}$ where f_{cav} and f_{pilot} are the cavity and pilot tone frequencies, and φ_{pilot} is the phase shift resulting from the pilot tone PLL. During testing before the start of the FY10 run, we found that this method overcorrected at the cavity frequencies, and was worse for the high cavity frequencies that were farther away from the pilot tone frequency.

Additional testing confirmed that the phase shift due to the microwave link local oscillator was the dominant factor. The DSP software was modified so that it applies the same phase shift, the result from the PLL, at all frequencies.

To summarize the data flow, the FEC calculates periodic updates to the I/Q modulator settings based on the BTF measurements and writes amplitude and phase settings for each cavity to the shared memory on the DSP carrier board. The DSP reads the amplitude and phase from the shared memory, calculates and applies the additional phase shift based on the pilot tone PLL, converts the amplitude and phase to real and imaginary components, and writes these values to the FPGA on the ADC daughter card. These adjustments are performed at the same 10 kHz update rate as the PLL calculations. The FPGA generates the NIM Link data frames and sends them over the serial link to the I/Q modulators.

RESULTS

The pilot tone correction at the cavity frequencies was tested prior to the run with a synthetic beam signal. A signal from the network analyzer was transmitted over a fiber optic link to the pickup electronics and then back to the analyzer over the microwave link. The network analyzer was configured for zero span, and the phase of the received signal was monitored with the pilot tone corrections enabled and disabled. We were able to determine that applying the single phase correction at all

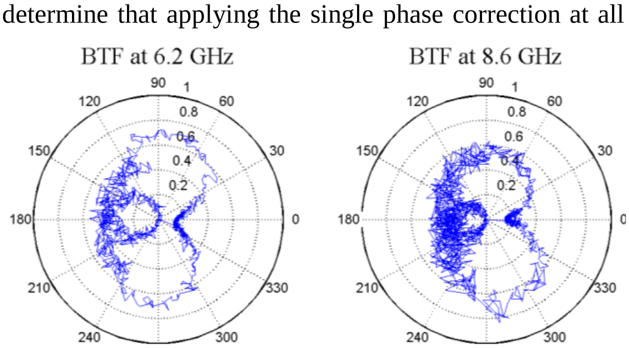

Figure 7: Beam transfer functions for 6.2 GHz and 8.6 GHz cavities.

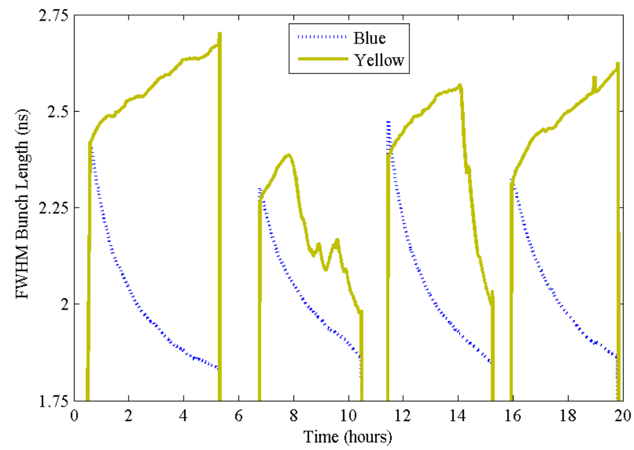

Figure 8: Evolution of the full width at half maximum bunch length in Blue and Yellow for four RHIC stores.

cavity frequencies significantly reduced the phase variation of the received signal. However, performance was degraded at the higher cavity frequencies. This indicates that there is some phase variation caused by the time of flight which is not currently compensated.

The phase compensation performance with beam was acceptable. The BTF measurements at the higher cavity frequencies exhibit more noise, consistent with the pre-run testing. This behavior is illustrated in figure 7. An additional test used the kicker to put a CW tone on the beam and measure the phase of the received signal after the phase correction was applied. The results of this test were consistent with the prior tests using the fiber optic link.

Figure 8 shows the performance of the longitudinal cooling system with the microwave link and pilot tone phase correction. Blue longitudinal cooling was on for all stores. Yellow longitudinal cooling was off for the first and last stores, and was being setup during the middle two stores. The shortened bunches improved the total luminosity and also increased the percentage of collisions in the center of the detectors, which enhances the efficiency of the PHENIX detector.

CONCLUSIONS

The microwave link allowed higher frequency operation of the longitudinal stochastic cooling system with better phase margin. A phase locked loop was successfully used to track an out of band pilot tone and apply phase corrections to the individual kicker cavity signals to compensate the phase modulation added by the link. We are developing an upgrade to the system to use tones at two frequencies to improve performance further.

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